# AMBER experiment's online filter system for virtualised IT infrastructure

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FACULTY OF NUCLEAR SCIENCES AND PHYSICAL ENGINEERING CTU IN PRAGUE

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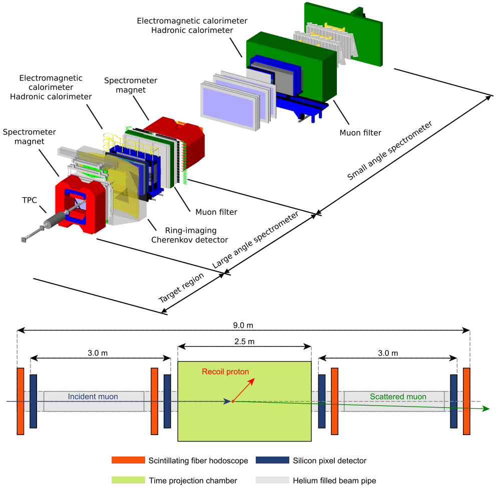
# Outline

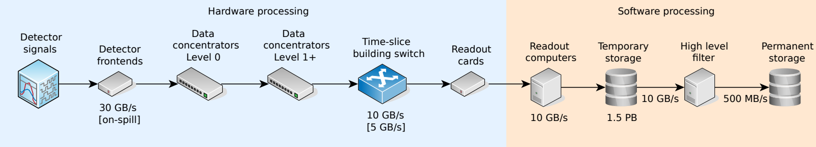
# AMBER experiment




- AMBER is a fixed target experiment located at the M2 beam line of the CERN SPS
- It has been approved by the CERN research board in 2021
- Measurement of the proton radius on an active hydrogen time projection chamber (TPC) with a muon beam is one of the objectives of the experiment
- Slow detectors (such as hydrogen TPC) have very long drift time (approx. 120 μs)
- They can handle only low trigger rates → need for a novel triggering approach

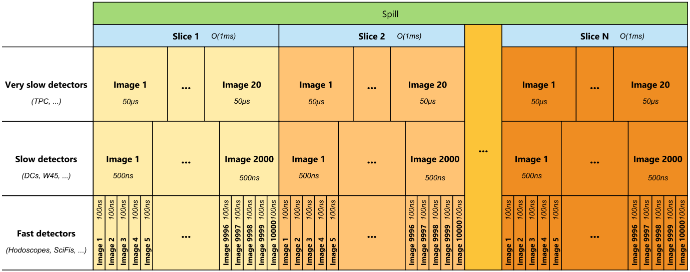
# Streaming readout system

- AMBER will use a trigerless data acquisition system based on continuous readout of detectors
- First stage relies on hardware-based processing in FPGA cards
- Second stage utilizes software developed with the Qt framework
- High-level filter is used instead of a low-level trigger logic
- General reduction scheme → any detector can participate in the filter decision



# Data structure

- We developed a custom streaming protocol consisting of several layers
- Data format consist of so-called time slices and images
- Global time slice signal is distributed to all detectors
- Images are generated individually based the detector time resolution
- Data reduction involves removing images that do not contain any physics events
- We store two consecutive images for every event candidate to prevent edge cases
- We expect a significant data reduction, aiming for a reduction factor of 100x



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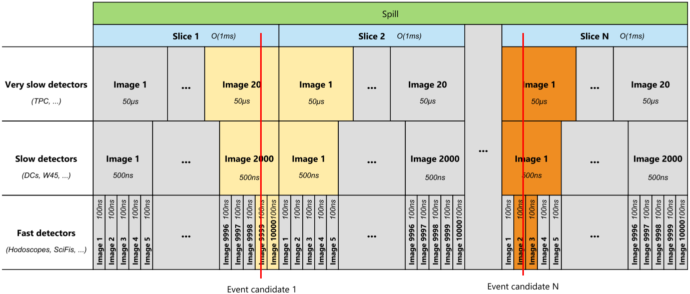
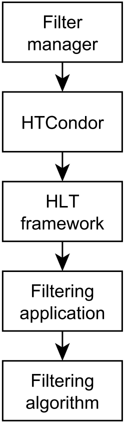


# High-level filter

- High-level filter is a distributed software platform for large-scale semi-online data filtering
- Filter runs on the virtualised CERN infrastructure shared with other users → significant cost optimization
- It consists of 2 main components:
  1. **Filter management system** (production system)
     - handles and manages individual requests
     - spawns instances of the filtering application
  2. **Filtering framework**
     - performs actual data analysis and reduction
     - includes additional tools for data browsing, quality monitoring

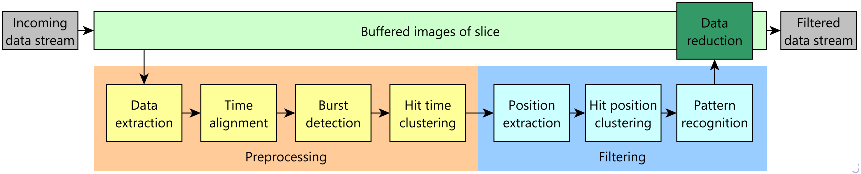
# Filtering framework

- High-throughput computational and reconstruction software written in optimized C++ and Qt
- It includes numerous libraries for various tasks such as data manipulation, detector alignment, database access, and more
- Algorithms vary depending on the current physics programme → modular architecture with many combinations
- Application optimizes the total performance through various methods:
  - Message-based thread communication
  - Non-uniform memory access (NUMA)
  - Adaptive multithreading
  - Zero-copy approach



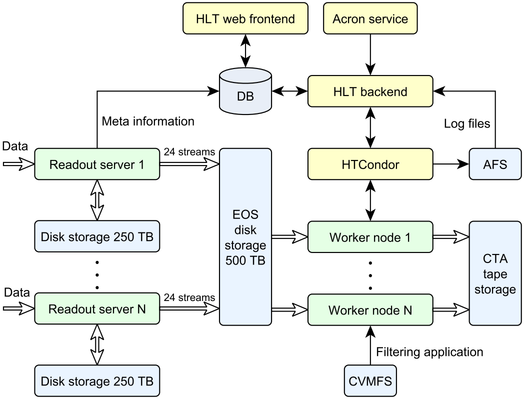
# Filtering pipeline

- We want to preserve and store only "interesting events"
- Such events can have different signatures, e.g., trajectories, coincidences, energy levels → track reconstruction is needed
- Initially, images are sorted into two exclusive groups:
  - **Primary images** – produced by detectors participating in filter decision
  - **Secondary images** – other images to be filtered
- We analyse primary images to make a decision using two phases:
  - **Time alignment** – processing and calibration of timestamps
  - **Spatial analysis** – analysis of hit positions to determine particle trajectory



# Filter management system

- Main task of management system is to handle filtering requests and follow them through the process
- It consists of two main parts:
  - **Backend** – based on HTCondor scheduling platform
  - **Frontend** – end user web application, serving as the main user interface
- Filtering system runs in the private CERN cloud shared with other experiments

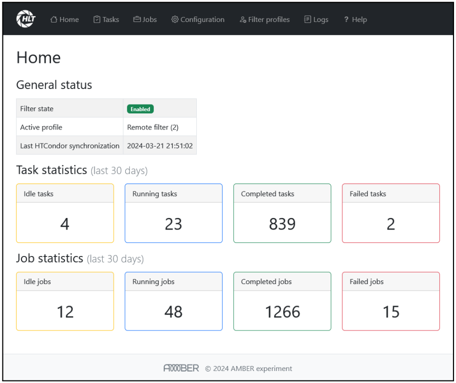


# Filter backend

- Python application is responsible for managing and submitting filtering jobs
- It relies on the HTCondor system as the primary execution platform
- HTCondor efficiently distributes computing tasks to connected machines → ensures scalability of our filter system
- CERN HTCondor instance hosts more than 100,000 CPU cores
- Jobs are synchronized through their lifecycle with HTCondor states
- Backend checks for any incoming requests every 2 minutes and submits filtering jobs to HTCondor

HTCondor Software Suite

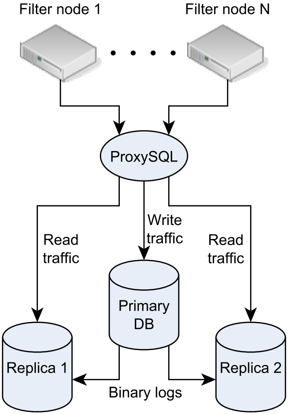
# Filter frontend



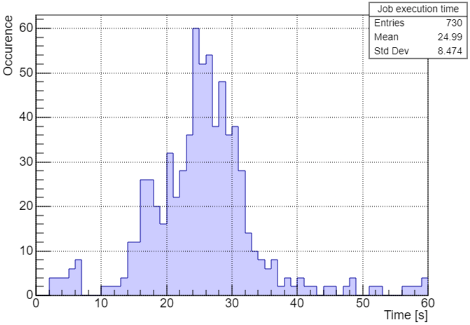

- Frontend is a web-based application for user interaction with the filter
- Users can control, monitor, and submits filtering tasks with custom parameters
- It provides monitoring and overview to operators on shift
- Tasks are automatically generated with predefined settings by default
- Filter also supports reprocessing of data files with different settings

# Configuration and database access

- During the filter operation, thousands instances of filtering application connect to the database simultaneously → we implemented a clustered database design
- It consists of a single primary database, two replicas, and ProxySQL load balancer
- MySQL caching mechanism quickly responds to any repetitive queries from nodes
- Database operates within a container on the Database-on-demand service
- Daily backups and recovery procedures are efficiently managed by the DBOD service



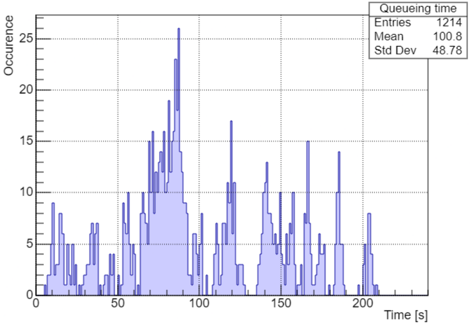
# Performance benchmark



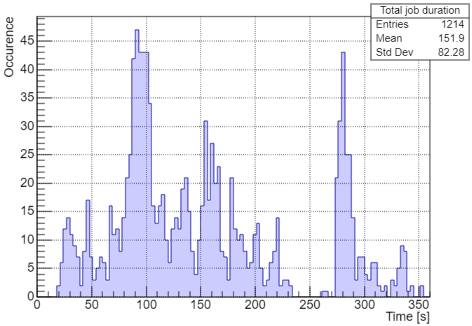

- We performed several tests and latency analysis of the filtering system
- Each file was processed by a single job running on 4 CPU cores
- Filtering a data file took **24.99 ± 8.47 seconds** on average
- Average processing rate is **10.24 MB/s**
- Considering 10 GB/s nominal data rate, we need roughly 1,000 CPU cores
- Processing rate depends on:
    - CPU performance,
    - used filter algorithm,
    - number of projections,
    - slice duration, etc.

# HTCondor queueing time

- Second measurement examined the queueing time in HTCondor
- Our initial tests indicates that a job spends around **100.80 ± 48.78 seconds** in the queue
- Variability is significant, almost 50 %
- Despite this volatility, the range of queueing times we observed is still within acceptable limits for our needs
- Queueing time is affected by:
  - cluster occupancy (other jobs),
  - job requirements (lower is better),
  - user priority (higher is better),
  - HTCondor quotas, etc.
- If queue times were to increase dramatically, we have several response strategies to address it



# Total job duration




- Third measurement focused on the total time taken for jobs to complete
- This includes factors like delays from the backend, file transfers, initialization processes, and so on
- On average, we found that jobs took about **151.90 ± 82.28 seconds** to complete
- Due to the limited statistical data, these measured values are preliminary
- Backend contributed an additional minute of latency on average due to 2 minute synchronization period

# Summary

- We designed the streaming acquisition system for the AMBER experiment at CERN
- System includes the custom data protocol and the high-level filtering framework replacing the low-level trigger
- We developed a scalable high-throughput filtering management system running on virtualised CERN infrastructure based on HTCondor, EOS, DBOD, CVMFS, and other services
- Performance of the filtering system has been measured and optimized
- System is capable of processing at least **10 GB/s** data rate in a semi-online manner with an average latency of **151.90 seconds**
- Filter will be used in the upcoming proton radius measurement later this year and will be further tested

# Thank you for your attention